# Geometric Design

CEE 320
Steve Muench

Dr. Ashraf El_Shahat

2011

# Outline

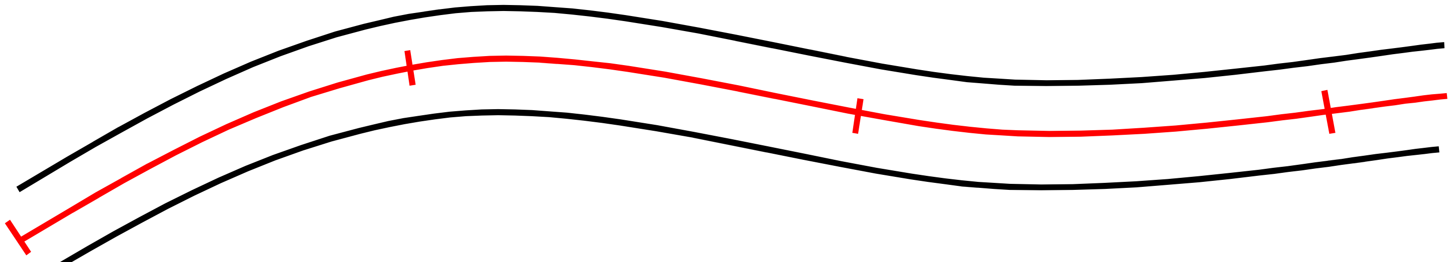
1. Concepts
2. Horizontal Alignment
   a. Fundamentals
   b. Superelevation
3. Setting out of Horizontal Curve

# Concepts

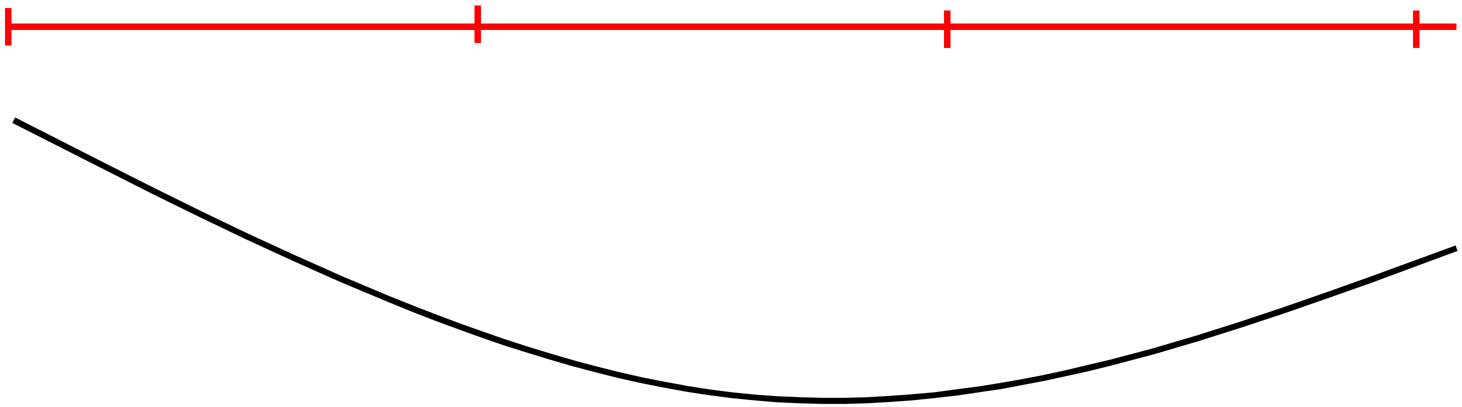
- **Alignment is a 3D problem broken down into two 2D problems**
  - **Horizontal Alignment (plan view)**
  - **Vertical Alignment (profile view)**
- **Stationing**
  - **Along horizontal alignment**
  - **12+500 = 12500 m.**

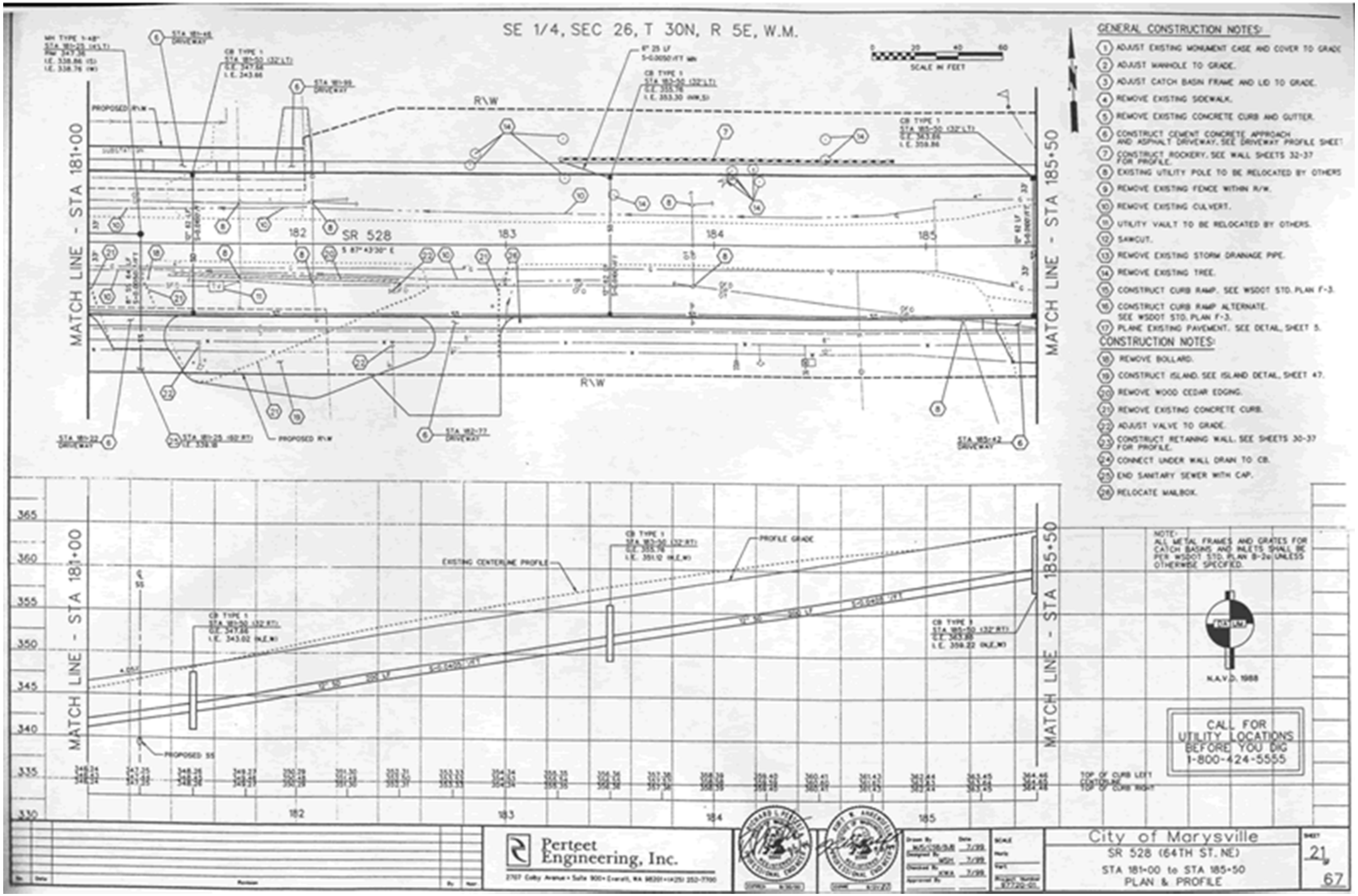
# Stationing

Horizontal Alignment

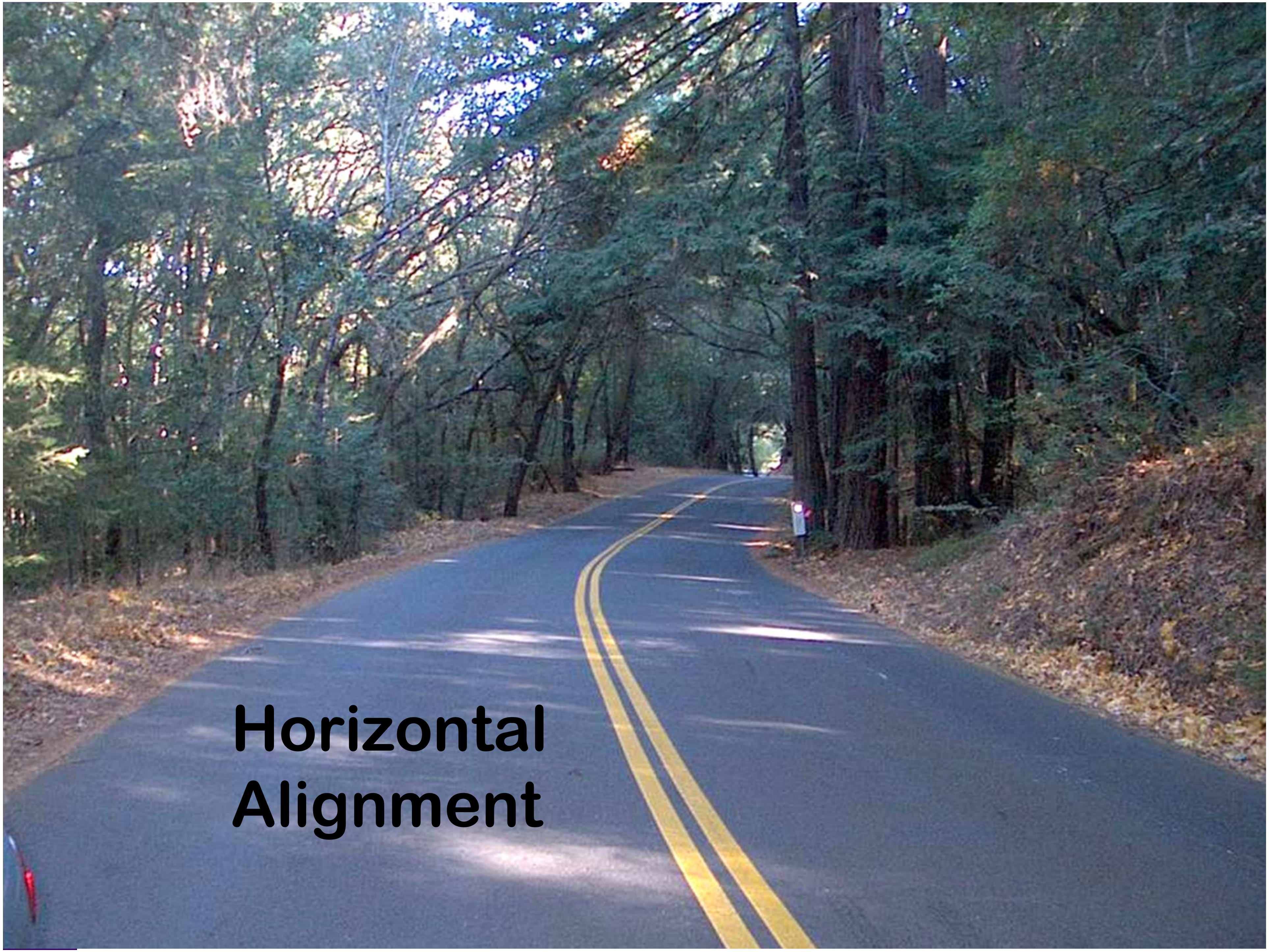


Vertical Alignment



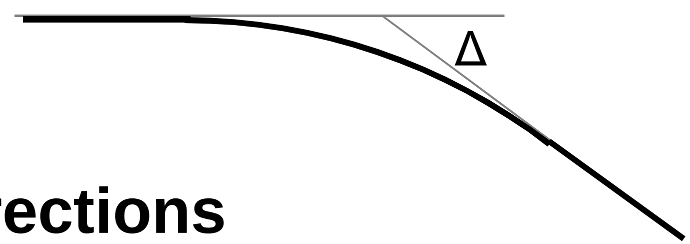



From Perteet Engineering


Horizontal
Alignment

# Horizontal Alignment

- **Objective:**
  - **Geometry of directional transition to ensure:**
    - **Safety**
    - **Comfort**



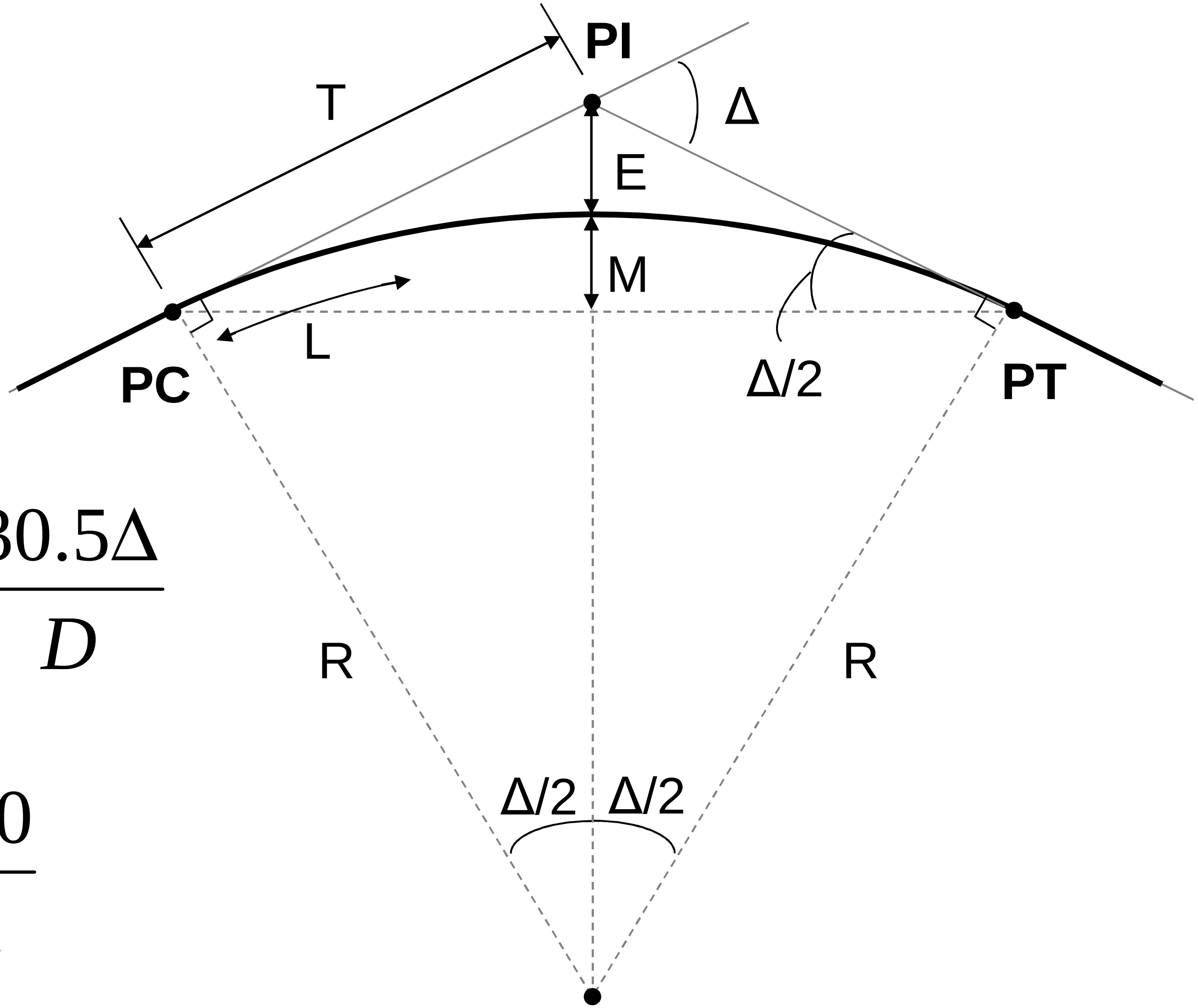

- **Primary challenge**
  - **Transition between two directions**
  - **Horizontal curves**
- **Fundamentals**
  - **Circular curves**
  - **Superelevation**

# Horizontal Curve Fundamentals

$$T = R\tan\frac{\Delta}{2}$$

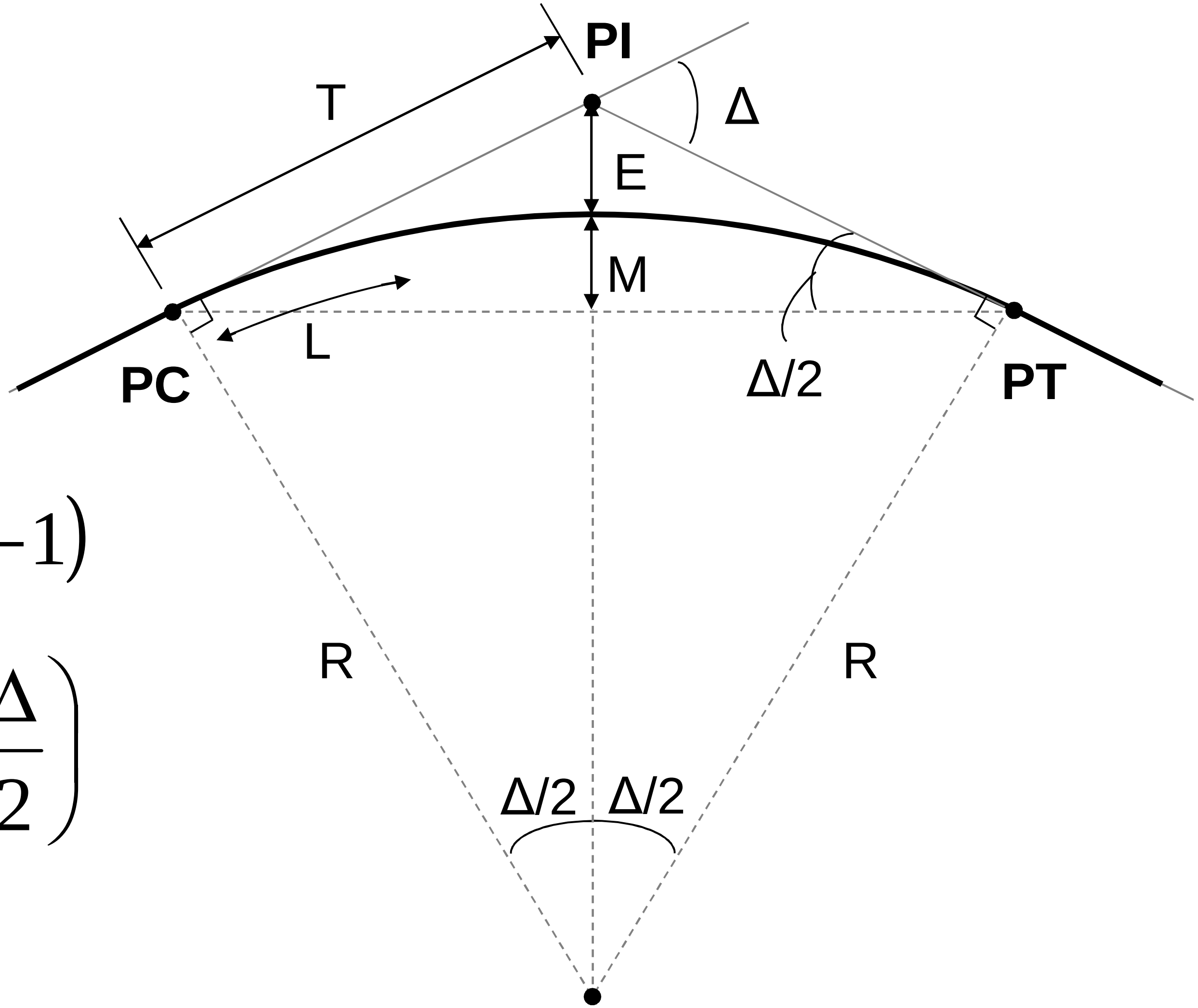
$$L = \frac{\pi}{180}R\Delta = \frac{30.5\Delta}{D}$$

$$D = \frac{1750}{R}$$




FAE_ZUN

# Horizontal Curve Fundamentals




$$E = R\left(Sec\Delta / 2 - 1\right)$$

$$M = R\left(1 - \cos\frac{\Delta}{2}\right)$$

FAE_ZUN


# Example 1

A horizontal curve is designed with a 450 m radius. The tangent length is 120m and the PC station is 2+000. What are the PI and PT stations?

# Design Concept

Two Basic Problems that determine the minimum radius of any horizontal curve.

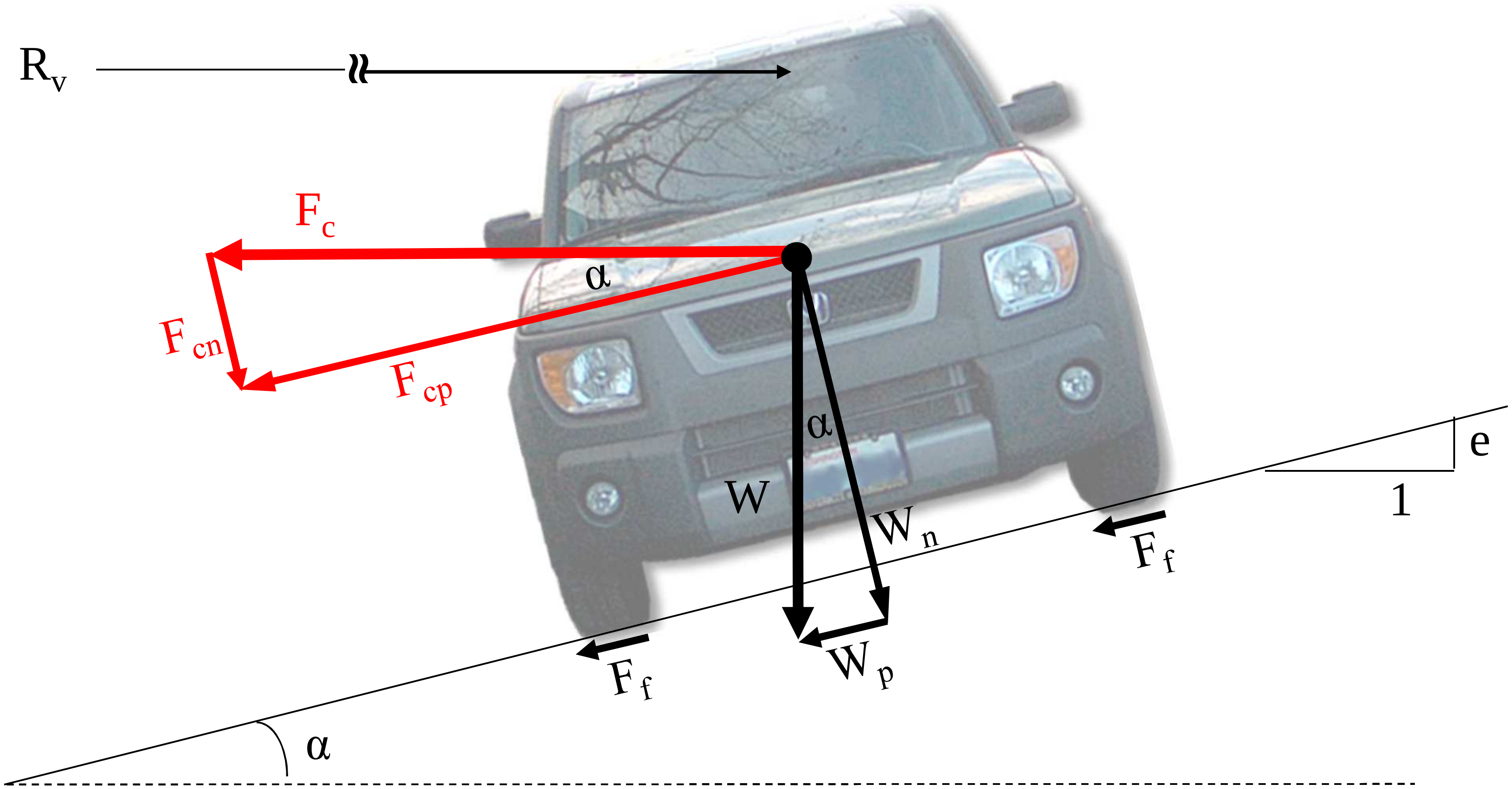

- Balance of vehicle , and


- Sight Distance .

# 1. Balance of vehicle (Superelevation)

# Superelevation

$$W_p + F_f = F_{cp}$$




$$W \sin\alpha + f_s\left(W\cos\alpha + \frac{WV^2}{gR_v}\sin\alpha\right) = \frac{WV^2}{gR_v}\cos\alpha$$

# Centripetal or Centrifugal?

- **As a vehicle moves in a circular path**
  - **Centripetal acceleration acts on the vehicle in the direction of the center of the curve**
- **The acceleration is sustained by**
  - **Component of the vehicle's weight related to the roadway superelevation**
  - **Side friction developed between the vehicle's tires and the pavement surface**
  - **Or a combination of the two**

# Superelevation

$$W\sin\alpha + f_s\left(W\cos\alpha + \frac{WV^2}{gR_v}\sin\alpha\right) = \frac{WV^2}{gR_v}\cos\alpha$$

$$\tan\alpha + f_s = \frac{V^2}{gR_v}\left(1 - f_s\tan\alpha\right)$$

$$e + f_s = \frac{V^2}{gR_v}\left(1 - f_s e\right)$$

$$e + f_s = \frac{V^2}{127R}$$

# Centrifugal Force

- **Imaginary force that drivers believe is pushing them outward while maneuvering a curve**
- **In fact, the force they feel is the vehicle being accelerated inward towards the center of the curve**

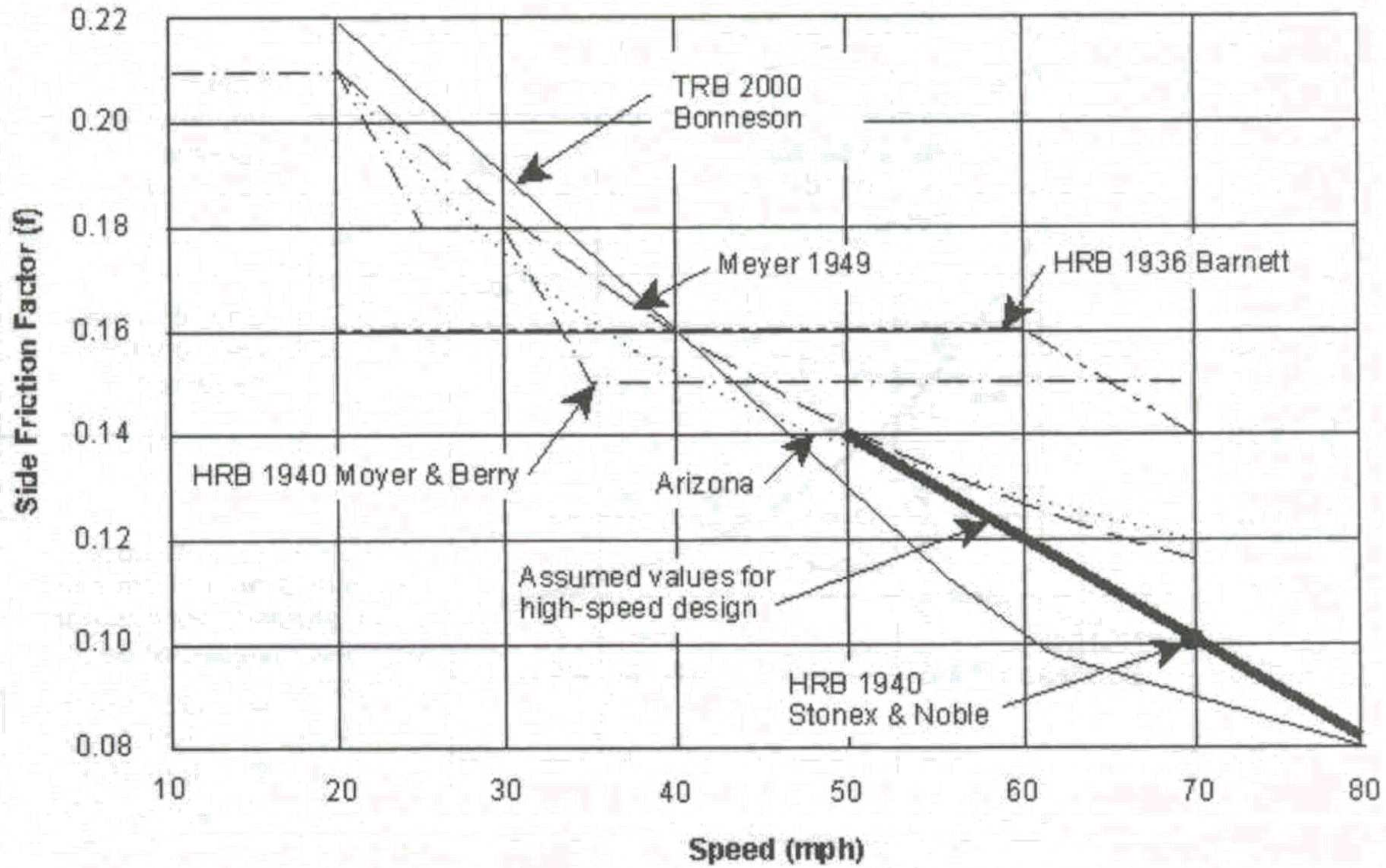
# Centripetal Acceleration

- Is counter-balanced by two factors:
  - Superelevation
  - Side Friction Factor
- Research has been conducted (dated) that has established limiting values for superelevation rate (e max) and side friction demand (f max)
- Applying the limiting values results in the minimum curve radius for various design speeds

# Selection of e and $f_s$

- **Practical limits on superelevation (e)**
  - Climate
  - Constructability
  - Adjacent land use
- **Side friction factor ($f_s$) variations**
  - Vehicle speed
  - Pavement texture
  - Tire condition

# Side Friction Factor ‘f’




From AASHTO’s *2004*

FAE_ZUN

Dr. Ashraf El_Shahat

2011


# Minimum Radius Tables $e_{max} = 4\%$

| الحد الأدنى لنصف القطر ($R_{min}$) عند ($V_d$) تساوي | | | | | | | | | الرفع الجانبي |
|---|---|---|---|---|---|---|---|---|---|
| **100** | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | **(e), %** |
| **3250** | **2640** | **2170** | **1740** | **1310** | **951** | **679** | **371** | **163** | **1.5** |
| **2260** | **1830** | **1490** | **1180** | **877** | **632** | **441** | **237** | **102** | **2.0** |
| **1980** | **1590** | **1290** | **1020** | **749** | **534** | **363** | **187** | **75** | **2.2** |
| **1730** | **1390** | **1110** | **865** | **626** | **435** | **273** | **132** | **51** | **2.4** |
| **1510** | **1200** | **944** | **720** | **508** | **345** | **209** | **99** | **38** | **2.6** |
| **1320** | **1030** | **802** | **605** | **422** | **283** | **167** | **79** | **30** | **2.8** |
| **1150** | **893** | **690** | **516** | **356** | **236** | **137** | **64** | **24** | **3.0** |
| **1010** | **779** | **597** | **443** | **303** | **199** | **114** | **54** | **20** | **3.2** |
| **879** | **680** | **518** | **382** | **260** | **170** | **96** | **45** | **17** | **3.4** |
| **767** | **591** | **448** | **329** | **222** | **144** | **81** | **38** | **14** | **3.6** |
| **658** | **505** | **381** | **278** | **187** | **121** | **67** | **31** | **12** | **3.8** |
| **492** | **375** | **280** | **203** | **135** | **86** | **47** | **22** | **8** | **4.0** |

From AASHTO's *2004*

Dr. Ashraf El_Shahat

2011

# Minimum Radius Tables $e_{max}$ = 6%

| الحد الأدنى لنصف القطر ($R_{min}$) عند ($V_d$) تساوي | | | | | | | | | | | | الرفع الجانبي |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 130 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | (e), % |
| 5240 | 4770 | 4060 | 3510 | 2880 | 2360 | 1910 | 1440 | 1050 | 738 | 421 | 194 | 1.5 |
| 3550 | 3510 | 2970 | 2560 | 2090 | 1710 | 1380 | 1030 | 750 | 525 | 299 | 138 | 2.0 |
| 3500 | 3160 | 2670 | 2300 | 1880 | 1530 | 1230 | 919 | 668 | 465 | 265 | 122 | 2.2 |
| 3190 | 2870 | 2420 | 2080 | 1700 | 1380 | 1110 | 825 | 599 | 415 | 236 | 109 | 2.4 |
| 2930 | 2630 | 2210 | 1890 | 1540 | 1260 | 1000 | 746 | 540 | 372 | 212 | 97 | 2.6 |
| 2700 | 2420 | 2020 | 1730 | 1410 | 1150 | 910 | 676 | 488 | 334 | 190 | 87 | 2.8 |
| 2510 | 2240 | 1870 | 1590 | 1290 | 1050 | 831 | 615 | 443 | 300 | 170 | 78 | 3.0 |
| 2330 | 2080 | 1730 | 1470 | 1190 | 959 | 761 | 561 | 402 | 269 | 152 | 70 | 3.2 |
| 2180 | 1940 | 1600 | 1360 | 1100 | 882 | 697 | 511 | 364 | 239 | 133 | 61 | 3.4 |
| 2050 | 1810 | 1490 | 1260 | 1020 | 813 | 640 | 465 | 329 | 206 | 113 | 51 | 3.6 |
| 1930 | 1700 | 1390 | 1170 | 939 | 749 | 586 | 422 | 294 | 177 | 96 | 42 | 3.8 |
| 1820 | 1590 | 1300 | 1090 | 870 | 690 | 535 | 380 | 261 | 155 | 82 | 36 | 4.0 |
| 1720 | 1500 | 1220 | 1010 | 806 | 635 | 488 | 343 | 234 | 136 | 72 | 31 | 4.2 |
| 1630 | 1410 | 1140 | 938 | 746 | 584 | 446 | 311 | 210 | 121 | 63 | 27 | 4.4 |
| 1540 | 1330 | 1070 | 873 | 692 | 538 | 408 | 382 | 190 | 108 | 56 | 24 | 4.6 |
| 1470 | 1260 | 997 | 812 | 641 | 496 | 374 | 258 | 172 | 97 | 50 | 21 | 4.8 |
| 1400 | 1190 | 933 | 755 | 594 | 457 | 343 | 235 | 156 | 88 | 45 | 19 | 5.0 |
| 1330 | 1120 | 871 | 701 | 549 | 421 | 315 | 214 | 142 | 79 | 40 | 17 | 5.2 |
| 1260 | 1060 | 810 | 648 | 506 | 386 | 287 | 195 | 128 | 71 | 36 | 15 | 5.4 |
| 1190 | 980 | 747 | 594 | 463 | 351 | 260 | 176 | 115 | 63 | 32 | 13 | 5.6 |
| 1110 | 900 | 679 | 537 | 416 | 315 | 232 | 156 | 102 | 56 | 28 | 11 | 5.8 |
| 951 | 756 | 560 | 437 | 336 | 252 | 182 | 123 | 79 | 43 | 21 | 8 | 6.0 |

From AASHTO's *2004*

# Minimum Radius Tables $e_{max}$ = 8%

| الحد الأدنى لنصف القطر ($R_{min}$) عند ($V_d$) تساوي | | | | | | | | | | | | (e), % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **130** | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | |
| 1220 | 1060 | 857 | 713 | 567 | 445 | 340 | 238 | 161 | 98 | 50 | 17 | 6.2 |
| 1180 | 1020 | 823 | 681 | 540 | 422 | 322 | 224 | 151 | 91 | 46 | 16 | 6.4 |
| 1140 | 982 | 789 | 651 | 514 | 400 | 304 | 210 | 141 | 85 | 43 | 15 | 6.6 |
| 1100 | 948 | 757 | 620 | 489 | 379 | 287 | 189 | 132 | 79 | 40 | 14 | 6.8 |
| 1070 | 914 | 724 | 591 | 464 | 358 | 270 | 185 | 123 | 73 | 37 | 13 | 7.0 |
| 1040 | 879 | 691 | 561 | 440 | 338 | 254 | 174 | 115 | 68 | 34 | 12 | 7.2 |
| 998 | 842 | 657 | 531 | 415 | 318 | 237 | 162 | 107 | 62 | 31 | 11 | 7.4 |
| 962 | 803 | 621 | 499 | 389 | 296 | 221 | 150 | 99 | 57 | 29 | 10 | 7.6 |
| 919 | 757 | 579 | 462 | 359 | 273 | 202 | 137 | 60 | 52 | 26 | 9 | 7.8 |
| 832 | 667 | 501 | 394 | 304 | 229 | 168 | 113 | 73 | 41 | 20 | 7 | 8.0 |

From AASHTO's *2004*

Dr. Ashraf El_Shahat

2011

# Minimum Radius Tables $e_{max}$ = 10%

| الحد الأدنى لنصف القطر ($R_{min}$) عند ($V_d$) تساوي | | | | | | | | | | | | (e)% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **130** | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | |
| 1280 | 1140 | 941 | 795 | 640 | 538 | 404 | 298 | 210 | 138 | 77 | 31 | 6.2 |
| 1240 | 1100 | 907 | 766 | 616 | 516 | 387 | 285 | 200 | 130 | 72 | 28 | 6.4 |
| 1200 | 1060 | 876 | 738 | 593 | 496 | 372 | 273 | 191 | 121 | 67 | 26 | 6.6 |
| 1170 | 1030 | 846 | 712 | 571 | 476 | 357 | 261 | 181 | 114 | 62 | 24 | 6.8 |
| 1130 | 993 | 819 | 688 | 551 | 458 | 342 | 249 | 172 | 107 | 85 | 22 | 7.0 |
| 1100 | 963 | 792 | 664 | 532 | 441 | 329 | 238 | 164 | 101 | 55 | 21 | 7.2 |
| 1070 | 934 | 767 | 642 | 513 | 425 | 315 | 228 | 156 | 95 | 51 | 20 | 7.4 |
| 1040 | 907 | 743 | 621 | 496 | 409 | 303 | 218 | 148 | 90 | 48 | 18 | 7.6 |
| 1010 | 882 | 721 | 601 | 479 | 394 | 291 | 208 | 141 | 85 | 54 | 17 | 7.8 |
| 981 | 857 | 699 | 582 | 463 | 380 | 279 | 199 | 135 | 80 | 43 | 16 | 8.0 |
| 956 | 834 | 679 | 564 | 448 | 366 | 268 | 190 | 128 | 76 | 40 | 15 | 8.2 |
| 932 | 812 | 660 | 546 | 432 | 353 | 257 | 182 | 122 | 72 | 38 | 14 | 8.4 |
| 910 | 790 | 641 | 528 | 417 | 339 | 246 | 174 | 116 | 68 | 36 | 14 | 8.6 |
| 888 | 770 | 621 | 509 | 402 | 326 | 236 | 166 | 110 | 64 | 34 | 13 | 8.8 |
| 867 | 751 | 602 | 491 | 386 | 300 | 225 | 158 | 105 | 61 | 32 | 12 | 9.0 |
| 847 | 731 | 582 | 472 | 371 | 287 | 215 | 150 | 99 | 57 | 30 | 11 | 9.2 |
| 828 | 709 | 560 | 453 | 354 | 274 | 204 | 142 | 94 | 54 | 28 | 11 | 9.4 |
| 809 | 685 | 537 | 432 | 337 | 259 | 192 | 133 | 88 | 50 | 26 | 10 | 9.6 |
| 786 | 656 | 509 | 407 | 316 | 242 | 1789 | 124 | 81 | 46 | 24 | 9 | 9.8 |
| 739 | 597 | 454 | 358 | 277 | 210 | 154 | 105 | 68 | 38 | 19 | 7 | 10.0 |

From AASHTO's *2004*

Dr. Ashraf El_Shahat

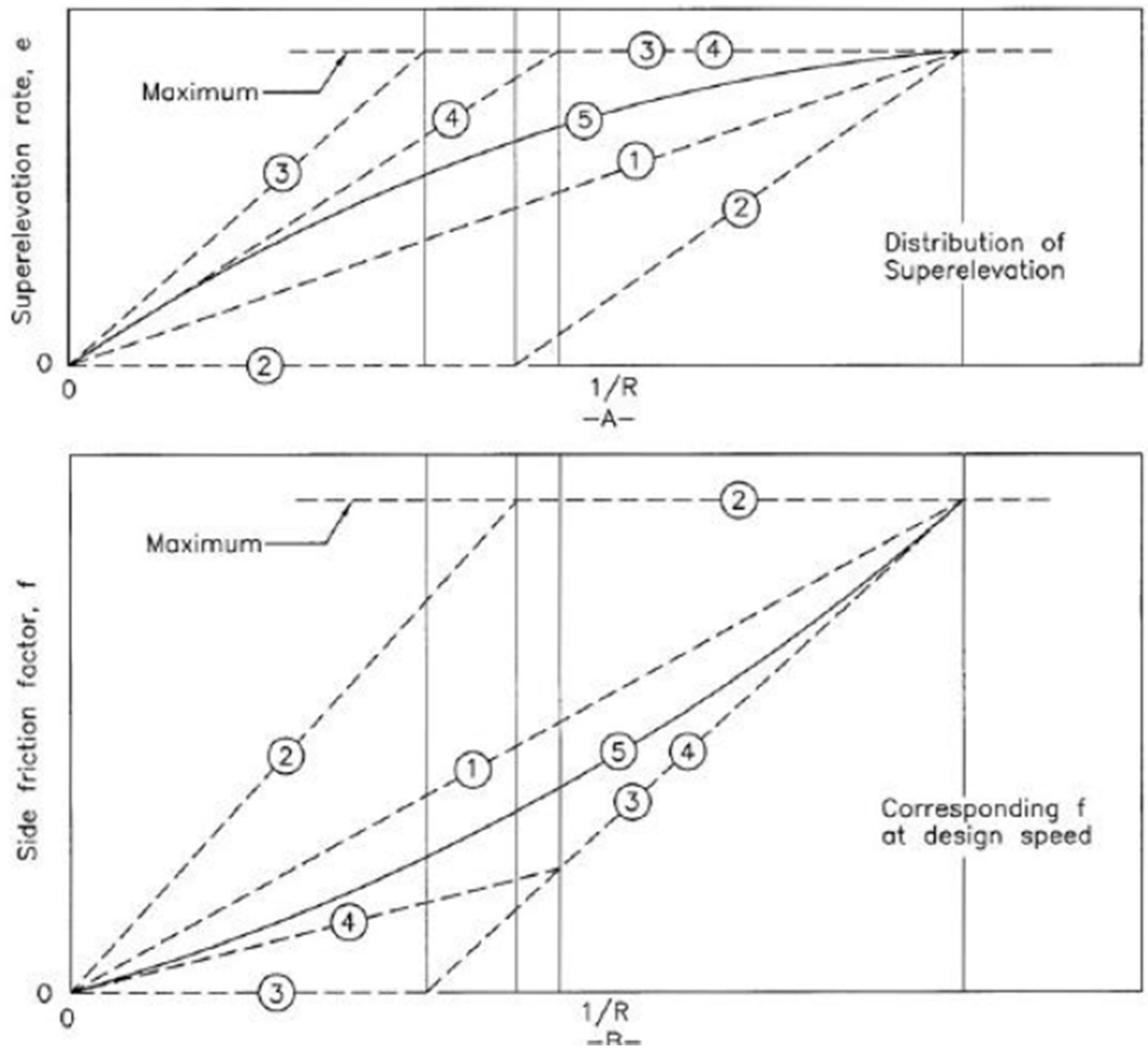
2011

# Minimum Radius Tables $e_{max}$ = 12%

| الحد الأدنى لنصف القطر ($R_{min}$) عند ($V_d$) تساوي | | | | | | | | | | | | (e), % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 130 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | |
| 1130 | 1010 | 834 | 708 | 572 | 462 | 364 | 270 | 192 | 128 | 71 | 32 | 7.2 |
| 1100 | 974 | 810 | 686 | 554 | 447 | 352 | 260 | 185 | 122 | 68 | 30 | 7.4 |
| 1070 | 947 | 786 | 666 | 537 | 433 | 340 | 251 | 178 | 117 | 65 | 29 | 7.6 |
| 1040 | 921 | 764 | 646 | 521 | 420 | 329 | 243 | 172 | 112 | 61 | 27 | 7.8 |
| 1020 | 897 | 743 | 628 | 506 | 402 | 319 | 235 | 165 | 107 | 58 | 26 | 8.0 |
| 989 | 874 | 723 | 610 | 491 | 395 | 306 | 227 | 159 | 102 | 55 | 24 | 8.2 |
| 965 | 852 | 704 | 593 | 477 | 383 | 399 | 219 | 154 | 97 | 52 | 23 | 8.4 |
| 942 | 831 | 686 | 577 | 464 | 372 | 390 | 212 | 148 | 93 | 50 | 22 | 8.6 |
| 921 | 811 | 668 | 562 | 451 | 361 | 381 | 205 | 142 | 88 | 473 | 20 | 8.8 |
| 900 | 792 | 652 | 547 | 439 | 351 | 273 | 198 | 137 | 85 | 45 | 19 | 9.0 |
| 880 | 774 | 636 | 533 | 428 | 341 | 264 | 191 | 132 | 81 | 43 | 18 | 9.2 |
| 861 | 756 | 621 | 520 | 416 | 332 | 256 | 185 | 127 | 77 | 41 | 18 | 9.4 |
| 643 | 739 | 606 | 507 | 406 | 323 | 249 | 179 | 123 | 74 | 39 | 17 | 9.6 |
| 826 | 723 | 592 | 494 | 395 | 314 | 241 | 173 | 118 | 71 | 37 | 16 | 9.8 |
| 809 | 708 | 579 | 482 | 385 | 305 | 234 | 167 | 114 | 68 | 36 | 15 | 10.0 |
| 793 | 693 | 566 | 471 | 375 | 296 | 226 | 161 | 110 | 65 | 34 | 14 | 10.2 |
| 778 | 679 | 553 | 459 | 365 | 288 | 219 | 155 | 105 | 62 | 33 | 14 | 10.4 |
| 763 | 665 | 541 | 448 | 355 | 279 | 212 | 150 | 101 | 59 | 31 | 13 | 10.6 |
| 749 | 652 | 529 | 436 | 345 | 270 | 204 | 144 | 97 | 57 | 30 | 12 | 10.8 |
| 735 | 639 | 516 | 423 | 335 | 261 | 197 | 139 | 93 | 54 | 28 | 12 | 11.0 |
| 722 | 626 | 503 | 411 | 324 | 252 | 189 | 133 | 89 | 51 | 27 | 11 | 11.2 |
| 709 | 613 | 488 | 397 | 312 | 242 | 182 | 127 | 85 | 49 | 25 | 11 | 11.4 |
| 697 | 598 | 472 | 397 | 300 | 232 | 173 | 120 | 80 | 46 | 24 | 10 | 11.6 |
| 685 | 579 | 453 | 382 | 285 | 219 | 163 | 113 | 75 | 43 | 22 | 9 | 11.8 |
| 665 | 540 | 414 | 364 | 255 | 194 | 143 | 98 | 64 | 36 | 18 | 7 | 12.0 |

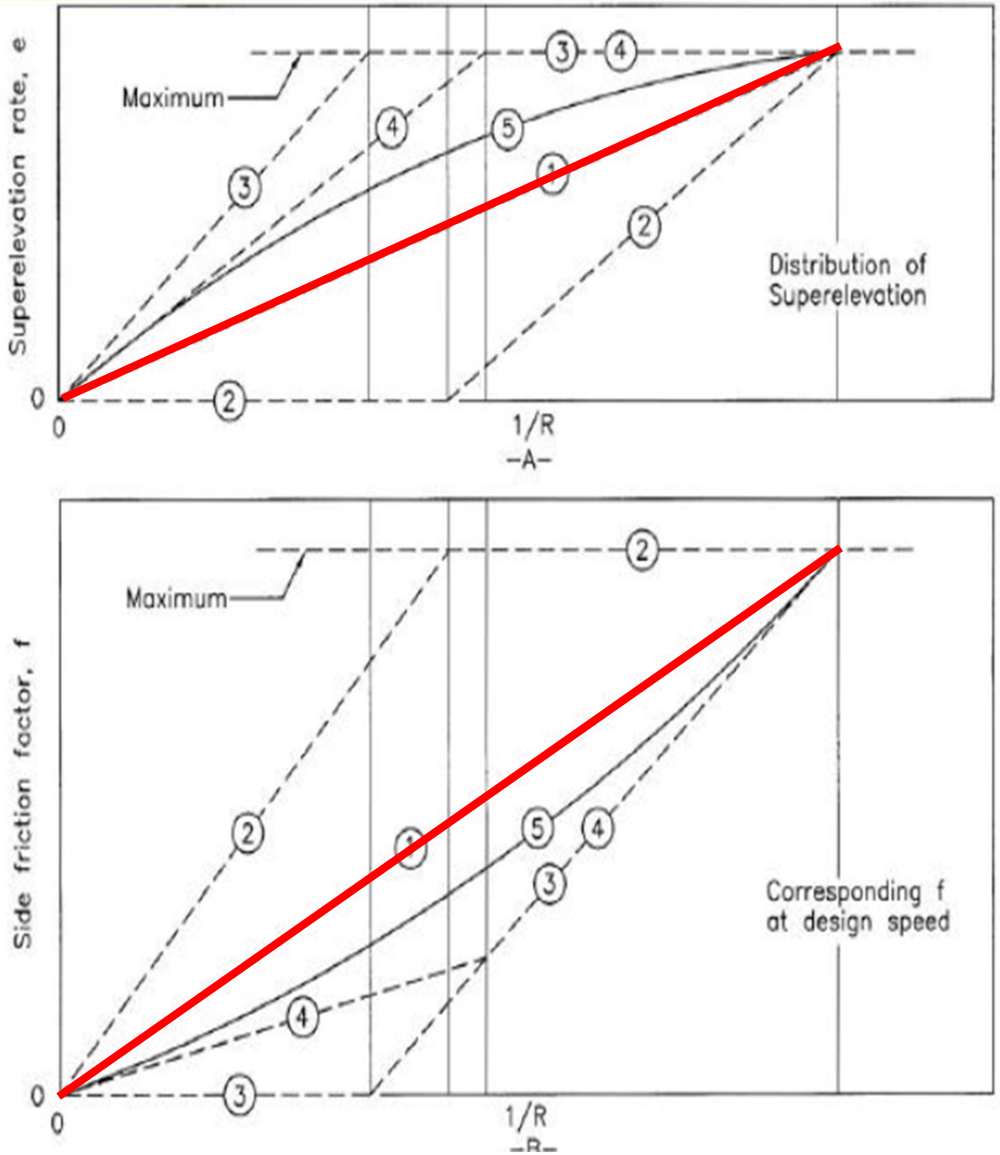
From AASHTO's *2004*

# Design Superelevation Rates - AASHTO



# Method 1: e and f are directly proportional to 1/R

- A straight line relation for e and f between 1/R=0 and $1/R=1/R_{min}$ for vehicles travelling at design or average running speed.
- Considerable merit and logic but simple.
- Appropriate if each vehicle travels at a constant speed on tangent and curve (intermediate degree or with minimum radius)
- Some drivers drive faster on tangents and flatter curves than on sharper curves.



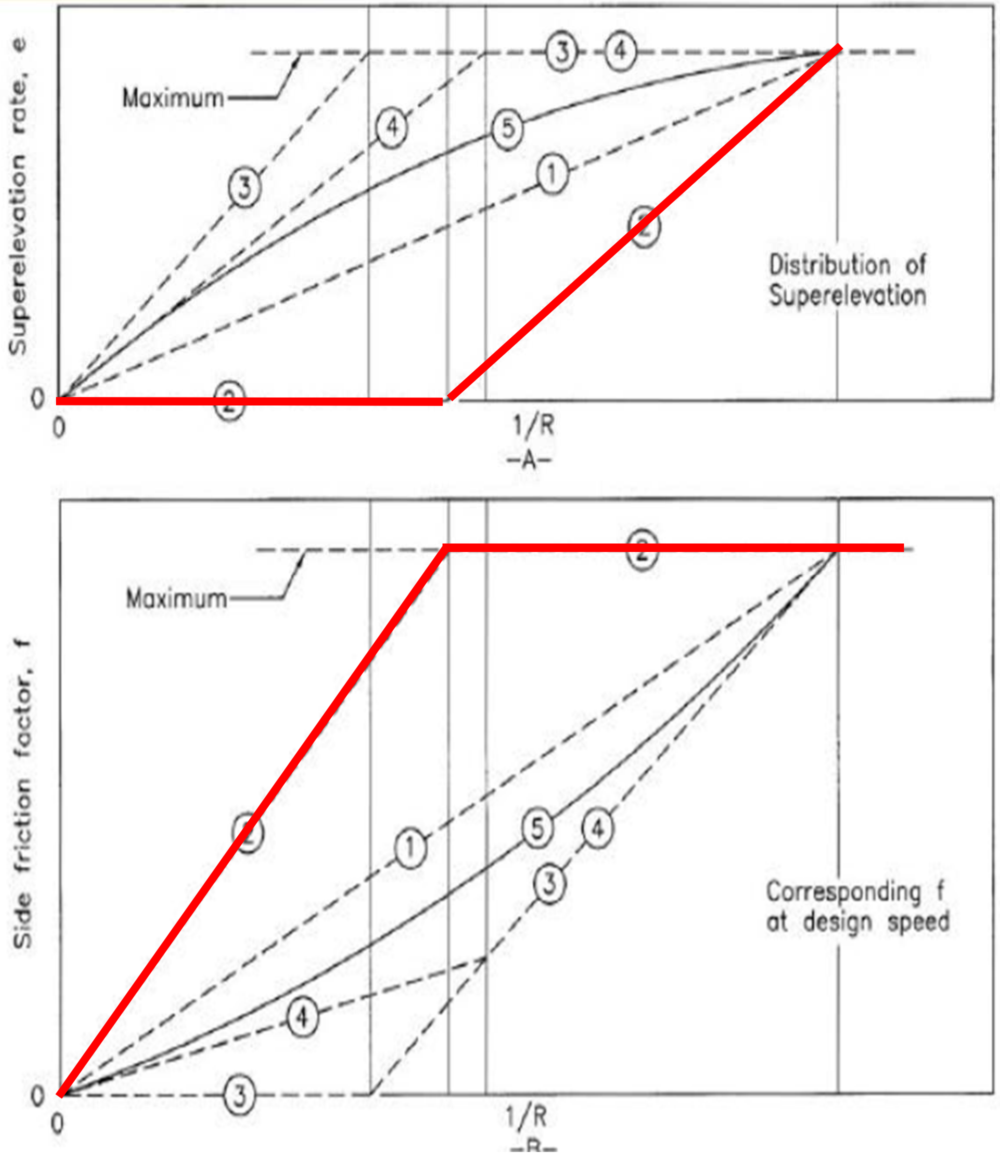
Dr. Ashraf El_Shahat

2011

FAE_ZUN

## Method 2: f first reaches the maximum value then e starts increasing

- First f - then e are increased in inverse proportion to the radius of curvature.
- Possibility of no superelevation on flatter curves.
- Superelevation, when introduced, increase rapidly.
- Particularly advantageous on low speed urban streets where because of practical constraints, superelevation frequently cannot be provided



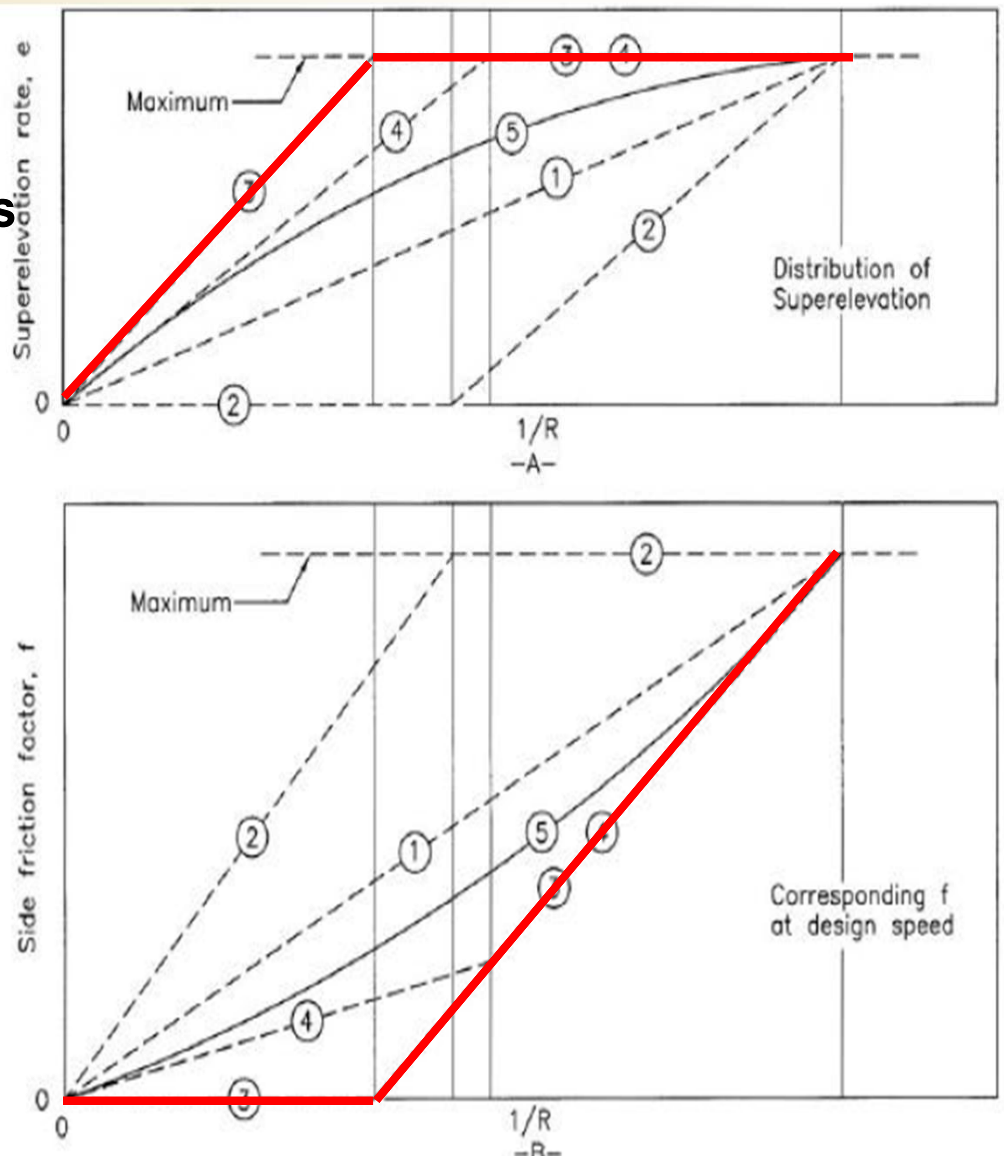
Dr. Ashraf El_Shahat

2011

FAE-ZUN

## Method 3: e first reaches the maximum value then f starts increasing

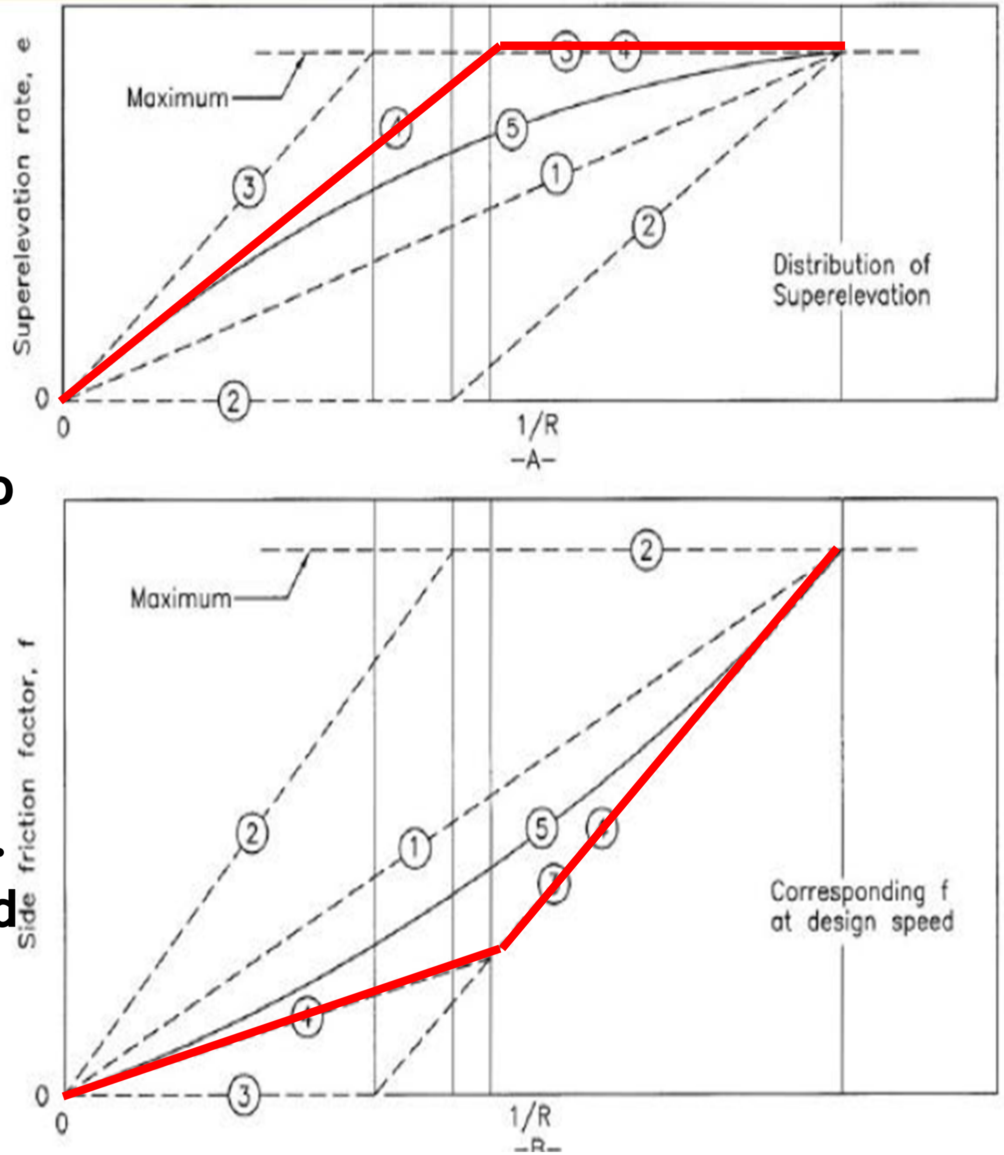
- e up to $e_{max}$ for vehicles travelling at design speed
- No side friction on flat curves ($e<e_{max}$ at design speed)
- Beyond $e_{max}$, f increase rapidly as curves become sharper.
- Results in negative f on flat curves for vehicles travelling at average running speed.
- Marked difference in f for different curves: Not logical and may result into erratic driving, either at design or average running speed.



# Method 4: Same as method 3

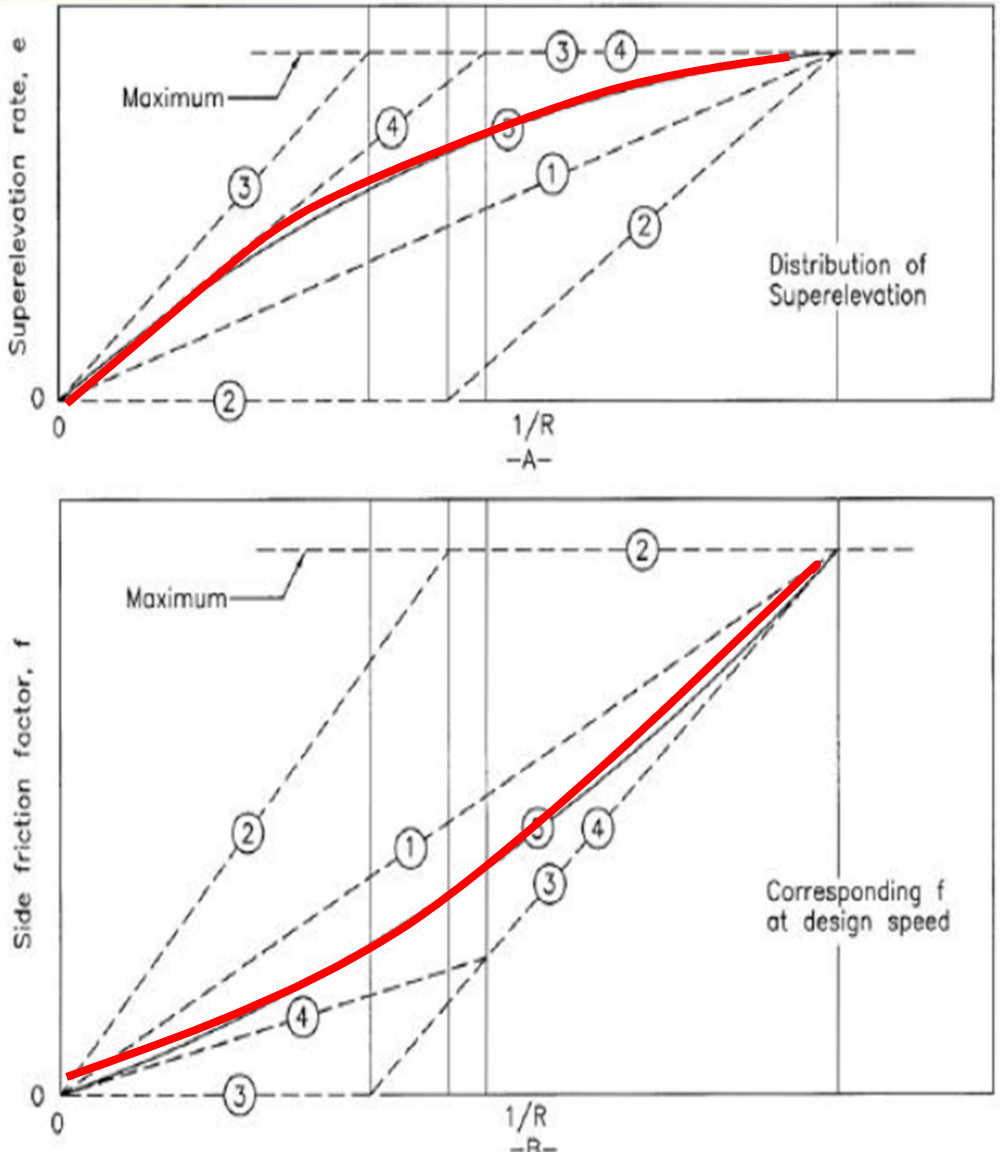
but this is based on average running speed instead of design speed

- Overcomes deficiency of method 3 by using e at speeds lower than design speed
- $e_{max}$ is reached near the middle of the curvature range
  - at average running speed no f is required up to this curvature.
- f, when introduced, increases rapidly and in direct proportion for sharper curves.
- Same disadvantage of method 3 but with smaller degree.



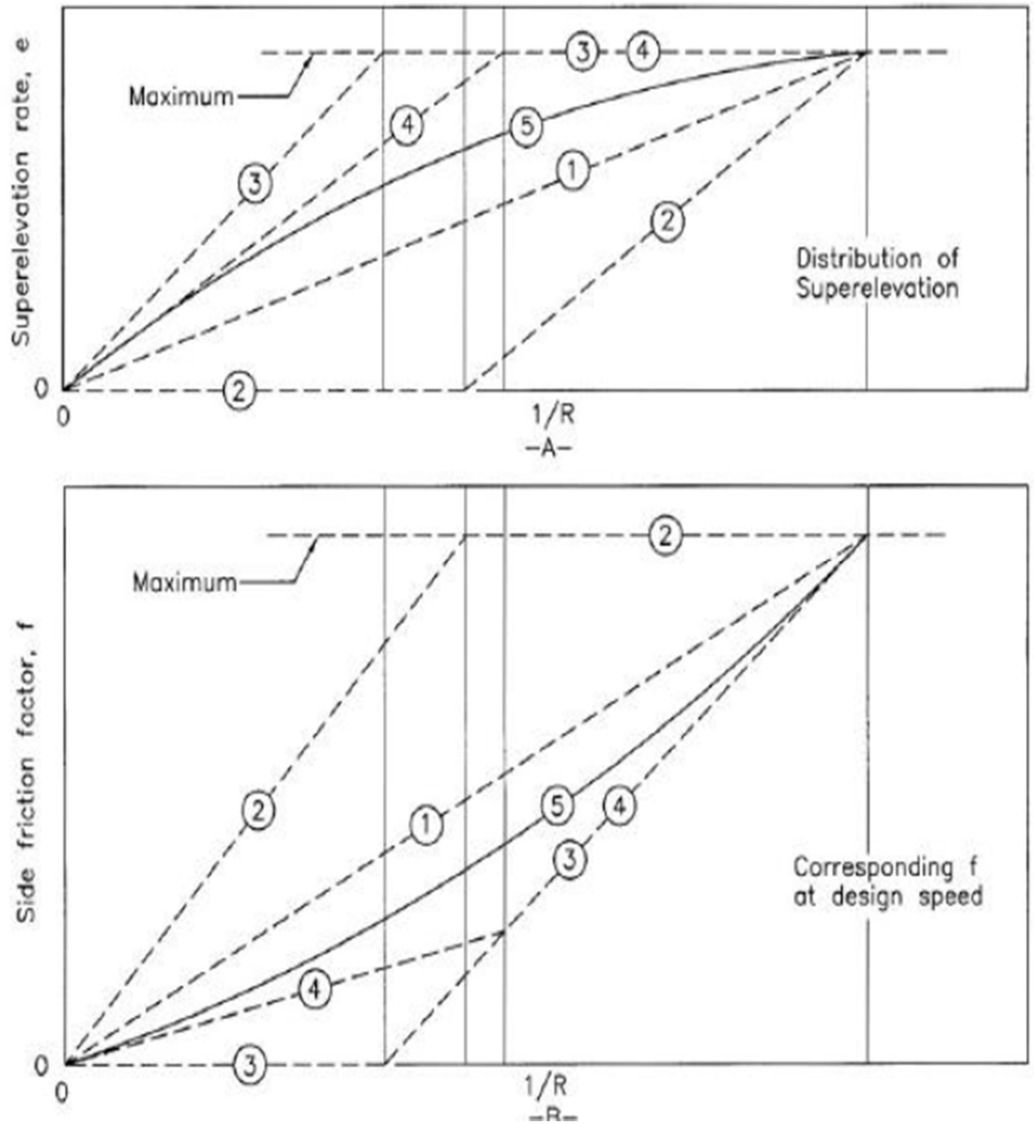
## Method 5: e and f are in a curvilinear relation with 1/R

- For overdriving (likely) on flat to intermediate curves: desirable to have ‘e’ similar to method 4.
- Very little risk for overdriving on such curves: ‘e’ adequate for average running speed and considerable ‘f’ for greater speed.



# Design Superelevation Rates - AASHTO

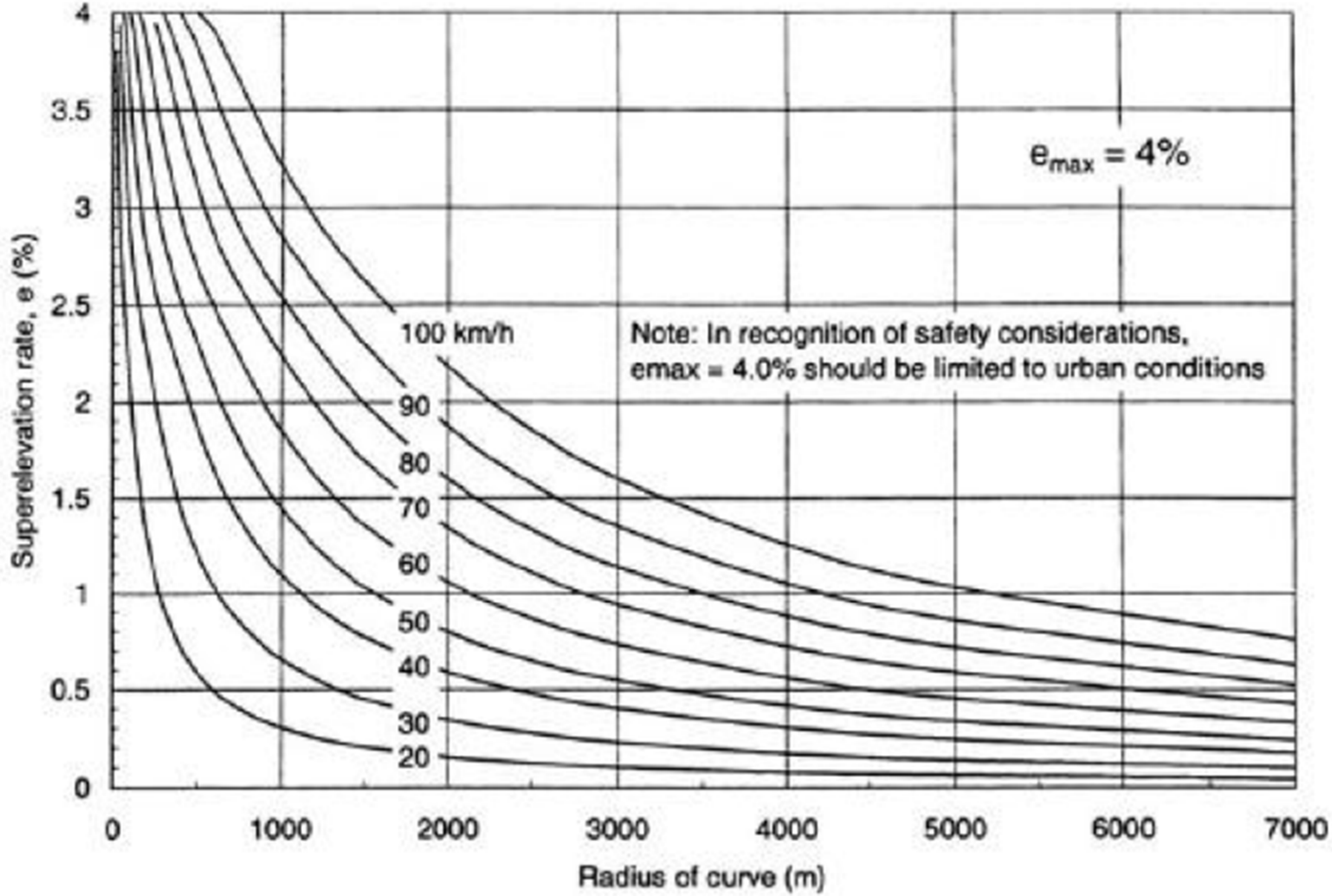
- Method 5: distribution of ‘e’ and ‘f’ reasonably retaining the advantages of both method 1and 4
- Method 1: is also desirable: a voids use of $e_{max}$ for a substantial part of the range of curve radii



Dr. Ashraf El_Shahat

2011

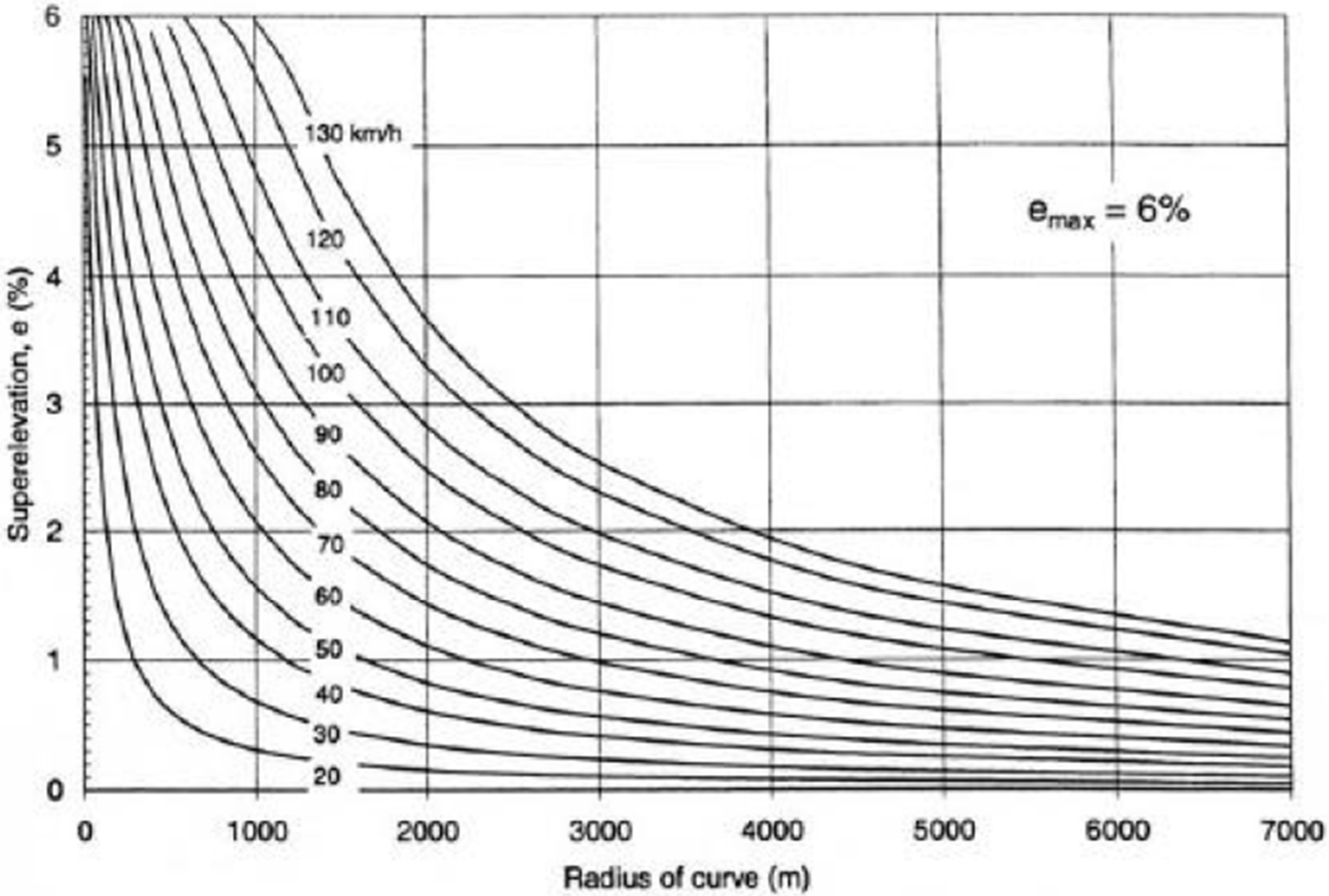
# Design Superelevation Rates - AASHTO



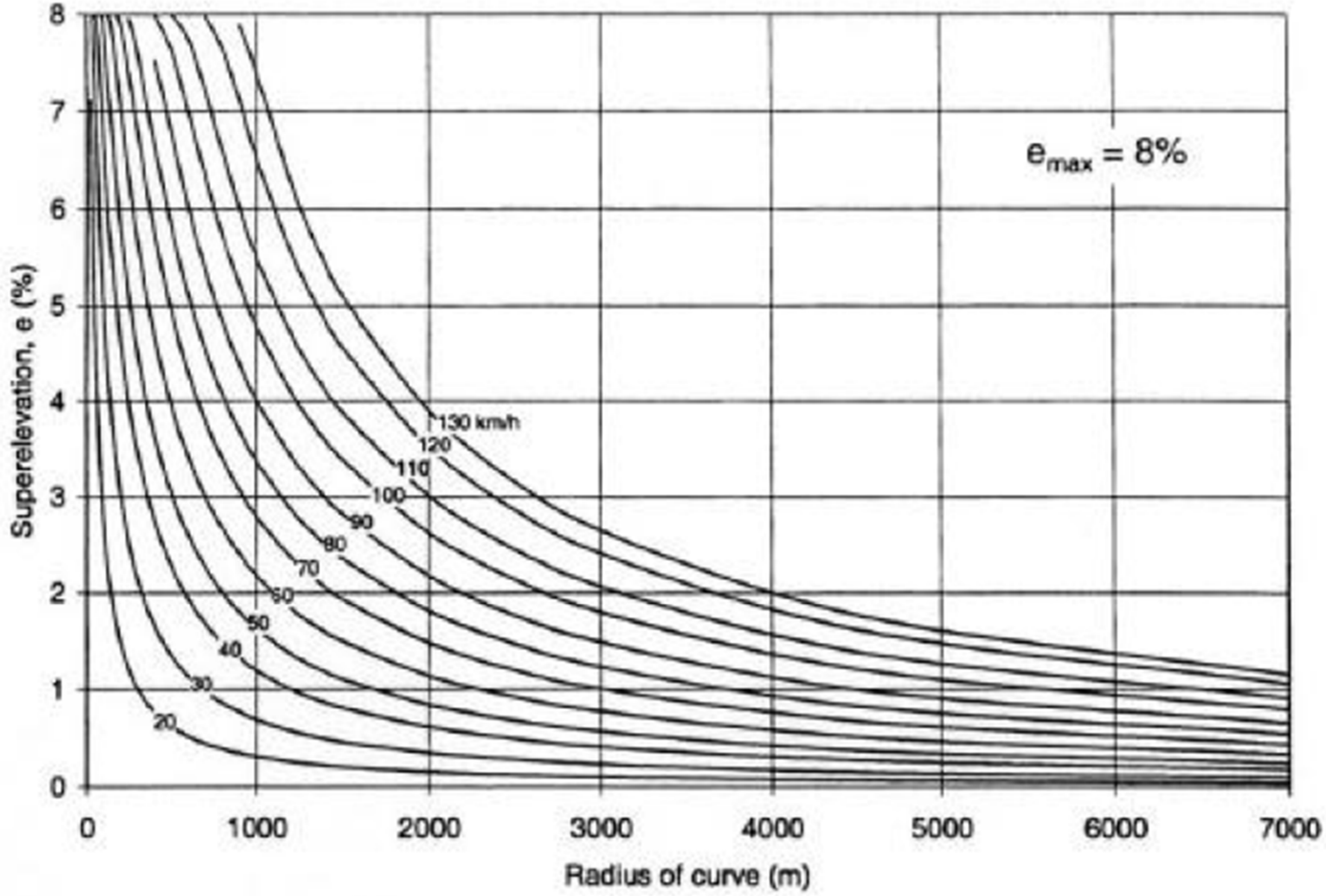

from AASHTO's *A Policy on Geometric Design of Highways and Streets 2004*

FAE_ZUN

# Design Superelevation Rates - AASHTO



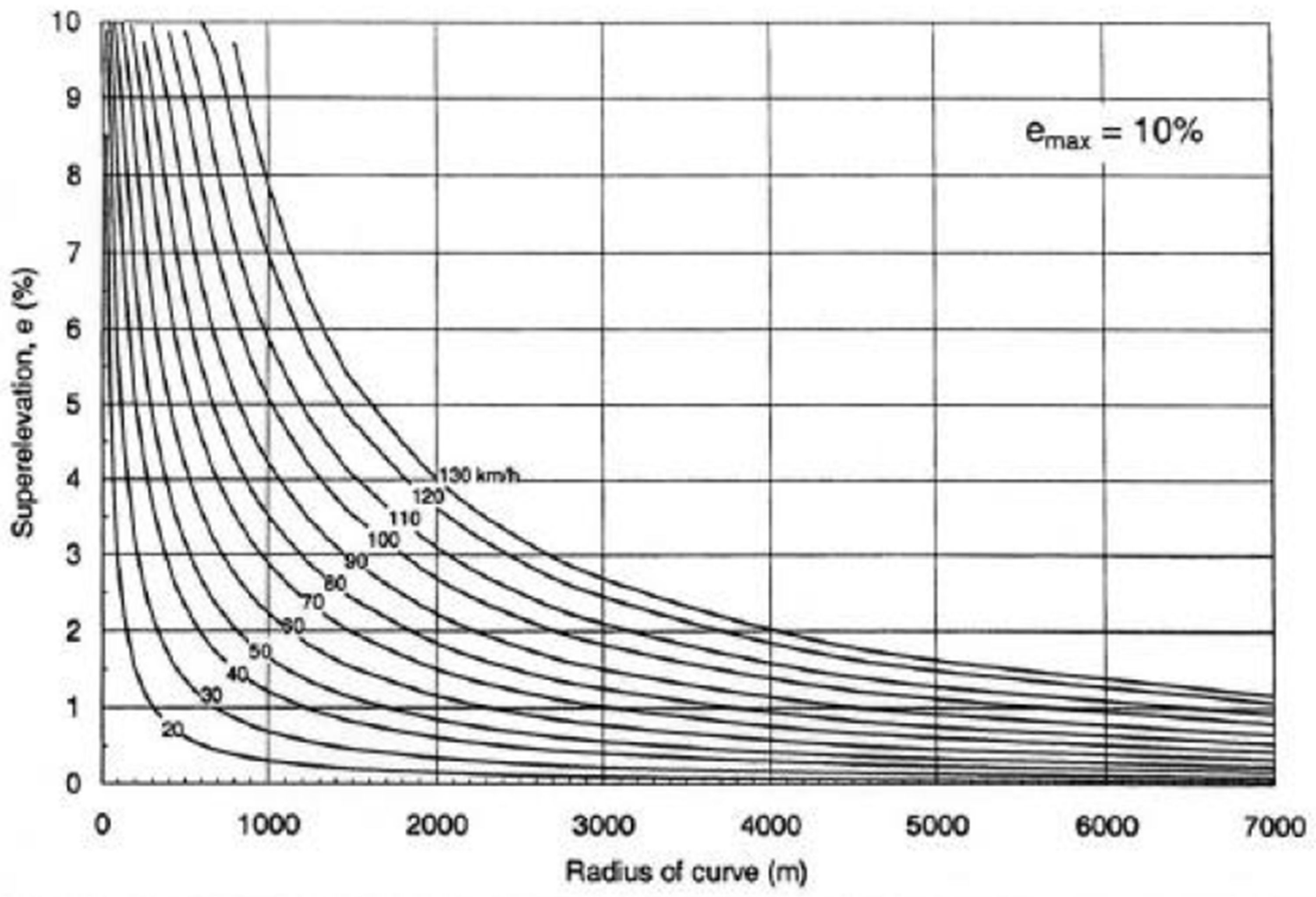
# Design Superelevation Rates - WSDOT




from the 2005 WSDOT *Design Manual*, M 22-01

FAE_ZUN

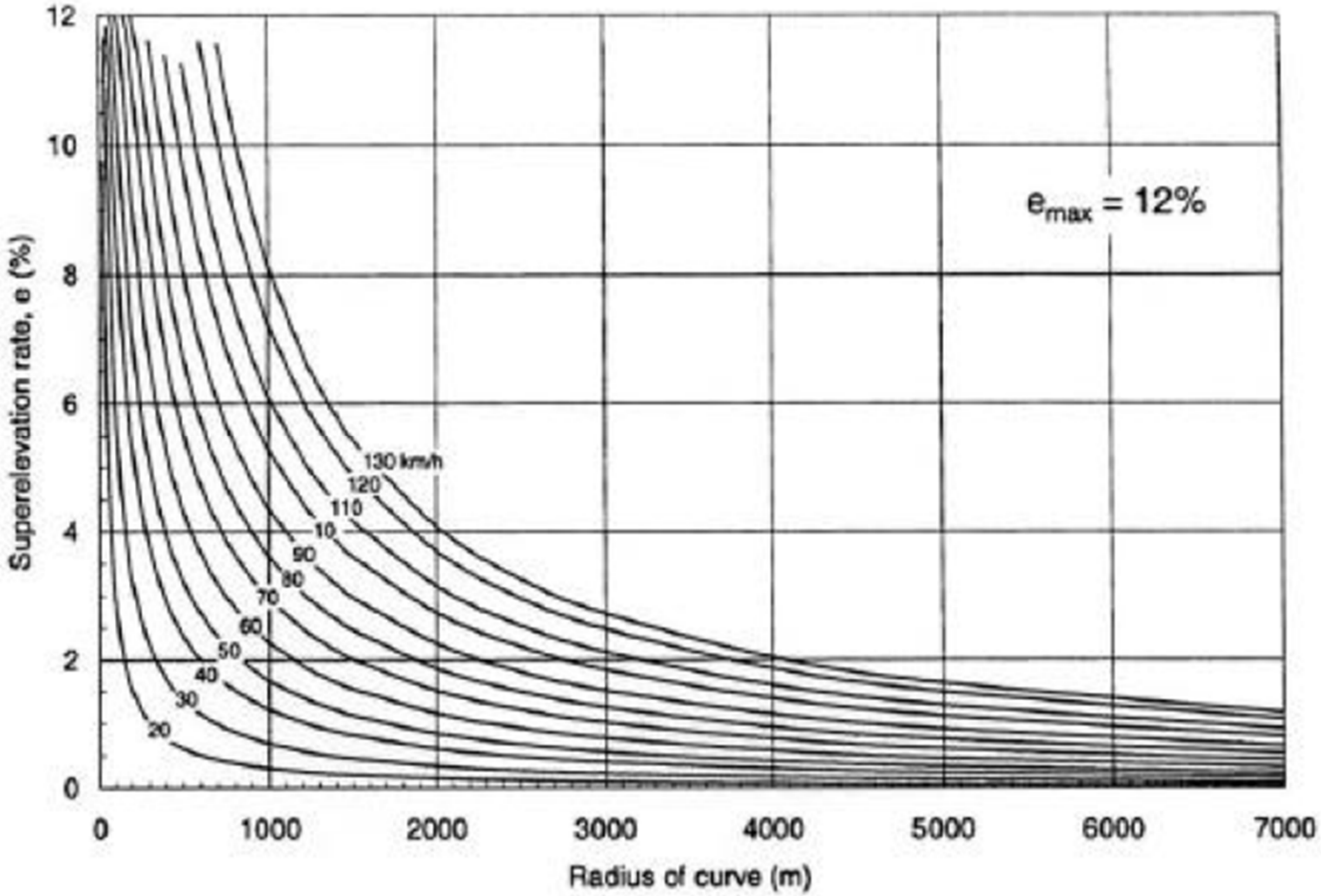
# Design Superelevation Rates - AASHTO



Dr. Ashraf El_Shahat

2011

# Design Superelevation Rates - AASHTO




FAE_ZUN

Dr. Ashraf El_Shahat 2011

# Maximum Superelevation (AASHTO)

1. Depending on four factors:
   - Climate condition (frequently & amount of snow and ice)
   - Terrain condition (flat, rolling, mountainous)
   - Type of area (Urban, Rural)
   - Frequently of slow moving vehicles (affect high 'e')
2. No single $e_{max}$ is universally applicable
3. Desirable to use one $e_{max}$ (uniformity) within a region and similar climate for design consistency

FAE-ZUN

# Maximum Superelevation (AASHTO)

Five values: 4, 6, 8, 10, 12 percent

- ✓ 12%: Practical maximum value where snow and ice do not exist
- ✓ 10%: Highest superelevation rate for highways in common use
- ✓ 8%: Reasonable max value for low volume gravel surfaces roads - also max practical limit where snow and ice are factors
- ✓ 4 - 6%: Where traffic congestion and extensive marginal development acts to restrict top speeds.

(above 8% only in areas without snow and ice)


# Example 5

A section of Blbs-Asher is being designed as a high-speed divided highway. The design speed is 100 kph. What is the minimum curve radius for safe vehicle operation?


# الحمـــــــد لله

# أي سؤال؟